

SCIENCE FOR GLASS PRODUCTION

UDC 691.618.54:666.1.038.1.001.24

ADEQUACY OF MATHEMATICAL MODELS OF THE GLASSWARE ANNEALING PROCESS

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The adequacy of the previously developed mathematical model of the glass tube annealing process is experimentally confirmed. The model is refined with respect to annealing of construction glass blocks by taking into account the effect of the barometric rarefaction inside the glass block air cavity on the process of the origin and distribution of stresses in the article, and the adequacy of the refined model is experimentally proved.

In order to effectively calculate the annealing conditions for glass articles and improve the technological equipment efficiency without deterioration of the quality of annealing, it is necessary to have the corresponding mathematical model describing the temperature field and stress field dynamics in a glass workpiece under heat treatment. The authors earlier constructed such mathematical models with respect to a glass tube and a glass building block and developed a synthesis algorithm for the most efficient annealing regime using these models [1–3]. In synthesis of the optimum annealing regime, certain deviations of the actual state of a glass article from the rated values arise due to the inevitable modeling error. Since implementation of the optimum annealing conditions is related to bringing the rate of glassware chilling to the maximum possible level, it can result in deterioration of the product quality.

The purpose of the present paper is to experimentally verify the previously developed mathematical models of annealing of glass products (glass tubes and structural glass blocks), to elucidate the extent of the inconsistency of these models with the real state of the glass products, and to develop the recommendations for taking into account the modeling error in synthesis of the optimum regime of glassware annealing.

The following articles were used in the experimental verification of the adequacy of the previously developed mathematical models of glass tubes and glass blocks annealing:

tubes made of P-15 glass (pyrex), wall thickness of 1.5 mm; inner diameter of 3.5, 12, 18, 30, and 42 mm, length of 300 mm, 10 pieces of each size;

tubes made of S-48-1 glass, wall thickness of 1.75 mm; inner diameter of 10, 20, 24, 29, and 38 mm, length of 300 mm, 10 pieces of each size;

tubes made of No. 23 glass, wall thickness of 1.0 mm; inner diameter of 5.5, 8, 10.5, 15, and 31 mm, length of 300 mm, 10 pieces of each size;

construction glass block BK 194/60 and its 1 : 2 model made of sheet glass.

The above listed articles were heat-treated according to the following condition: heating from 25 to 560°C at the heating rate of 1°C/min; isothermal holding for 1 hour at 560°C; cooling from 560 to 25°C at the rate of 5°C/min.

The heat treatment of the glassware was performed in a SNZ-3kh-6kh-2/10 electric resistance furnace, the air temperature in the furnace was monitored by a KSP-3P recording device. Next the maximum residual stresses in the glass articles were measured by a PSSK-250 polarimetric polariscope, and the stress distributions inside the wall of the glass block prototype were photographed. Unfortunately, it was impossible to make a photo of the stress distribution in the wall of the glass block proper, since the two thick walls of the glass block with light-scattering faces significantly reduced and distorted the polarized light flow passing through the glass block.

The obtained values of the maximum residual stresses in the glass tubes were averaged for each type and size. Using the previously developed mathematical model of the accepted heat-treatment regime for each type of tube, the estimated dependences of the maximum residual stresses on the tube inner diameter were obtained. The relaxation constants of the fictitious temperatures and stresses used in modeling were taken from [4], the thermal characteristics for each

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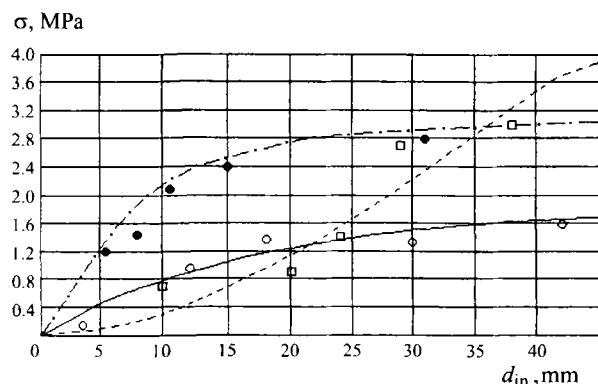


Fig. 1. Residual stresses in the glass tube versus the inner diameter. Glass No. 23: ●) experimental data; ---) calculated data; glass S-48-1: □) experimental data; ---) calculated data; glass P-15: ○) experimental data; —) calculated data.

glass tube were calculated using the methods described in [5], according to the compositions of glass components specified in [6]. The analysis of the theoretical and experimental data shown in Fig. 1 which specify the dependence of the maximum residual stresses on the tube inner diameter makes it possible to estimate the mean errors of the respective mathematical model for tubes made of different glass compositions: 3% for the P-15 glass model, 4% for No. 23 glass, and 8% for S-48-1 glass, which is equivalent to 5% on average.

The comparative analysis of stress distributions in the wall of the glass block prototype which were recorded in the photos or obtained through modeling of standard regime cooling revealed quantitative discrepancies in the stress values which amounted to 30% on average, and significant qualitative differences in stress distribution in the glass block prototype wall. Consequently, it was suggested that the errors were caused by the model's failure to take into account the effect of the air pressure difference outside and inside the glass block air cavity on the process of stress origin and distribution in the glass block.

By solving the problem of two-dimensional bending of a hinged rectangular plate under the effect of a uniformly distributed load (known as the Navier problem [7]), the authors introduced the corresponding adjustments to the previously developed mathematical model, which made it possible to account for the effect of the pressure difference on the stress variation dynamics in the glass block. After that the following procedures were carried out for airtight and non-airtight glass block prototypes: heat treatment according to the above described regime, photography of the residual stress distribution, determination of the rated residual stress distribution using the refined mathematical model. The resulting experimental and rated data are shown in Fig. 2. In both cases, the qualitative patterns of the distribution are similar, and the quantitative discrepancies in the stress values on average amount to 20%.

Thus, as a consequence of the solution of the problem, the adequacy of the previously developed mathematical model of glass tube annealing was proven within the speci-

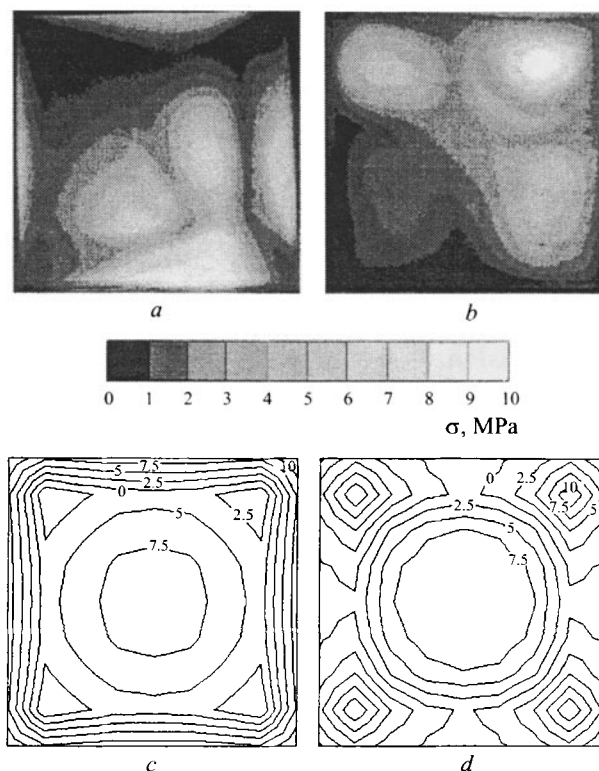


Fig. 2. Residual stress distribution in the wall of airtight (a) and non-airtight (b) prototypes of a construction glass block: a, b) experimental data; c, d) calculated data.

fied precision limits by taking into account the effect of the barometric rarefaction inside the air cavity on the stress variation dynamics in the glass article, the mathematical model of glass block annealing was refined, and its adequacy was established. According to the maximum residual stress values, the following errors for the specified models were revealed: 5% for the glass tubes, and 20% for the glass blocks. In synthesis of the optimum conditions of glassware annealing, these errors can be allowed for by increasing by a factor of 1.05 and 1.2, respectively, the restrictions imposed on the residual stress values.

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